Fossil Groups in the Sloan Digital Sky Survey

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ABSTRACT

A search for fossil groups in the Sloan Digital Sky Survey was performed using virtual observatory tools. A cross-match of the positions of all SDSS Luminous Red Galaxies (with r < 19 and measured spectroscopic redshifts) with sources in the ROSAT All-Sky Survey catalog resulted in a list of elliptical galaxies with extended X-ray emission (with a galaxy/ROSAT-source distance of less than 0.5 arcmin in all cases). A search for neighbors of the selected elliptical galaxies within a radius of $0.5h_{70}^{-1}$ Mpc was conducted taking into account the r-band magnitudes and spectroscopic or photometric redshifts of all objects within this area, leading to a sample of 34 candidate fossil groups. Considering this sample, the estimated space density of fossil systems is $n = (1.0 \pm 0.6) \times 10^{-6}\ h_{50}^3$ Mpc^{-3}.

Subject headings: astronomical data bases: miscellaneous — galaxies: elliptical and lenticular, cD — galaxies: clusters: general — X-rays: galaxies: clusters

1. Introduction

Fossil groups are systems with masses and X-ray luminosities comparable to those of groups and clusters of galaxies, but whose light is dominated by a single, isolated, large elliptical galaxy. Their denomination, "fossil", comes from their possible formation scenario in which they may have collapsed at an early epoch, being the oldest and most undisturbed galaxy systems not yet absorbed by larger halos.

Studies of fossil groups started fairly recently, the first system being identified by Ponman et al. (1994). They defined a fossil group as a system with a bright ($> 0.5 \times 10^{43}$ h$_{50}^{-2}$ erg s^{-1}) and extended X-ray halo, dominated by one brighter-than-L* elliptical galaxy which is surrounded by low-luminosity companions, where the difference in magnitude between the bright dominant elliptical and the next brightest companion is > -2 mag.

Fossil groups may have been formed by the complete merging of galaxies within once normal groups/clusters (Vikhlinin et al. 1999; Mulchaey & Zabludoff 1999). Indeed, this is consistent with the fact that

their baryon fraction is similar to that observed in clusters (Mathews et al. 2005). It has been suggested that a fossil group could be a collapsed *compact group* of galaxies, but the connection between compact and fossil groups is not obvious. From samples of today's compact groups, C. Mendes de Oliveira & E. R. Carrasco (2007, in preparation) argue that compact groups which are in the process of merging are those with the poorest neighborhoods and lowest velocity dispersions, not resembling the much more massive fossil group counterparts. X-ray studies of compact groups (Ebeling et al. 1994; Pildis et al. 1995; Ponman et al. 1996) have shown that although the majority are X-ray loud (Ponman et al. 1996 infer that a fraction of 75% of the sample of Hickson compact groups have hot intragroup gas), their X-ray luminosities and temperatures are much lower than those measured for typical fossil groups. More recently, Khosroshahi et al. (2007) have made a detailed comparison of the X-ray properties of fossil groups with those of other groups (see their Fig. 2) and have found that fossil groups have higher X-ray temperatures and

luminosities for a given L_R when compared with normal groups.

Two studies performed searches for fossil groups using well-defined selection criteria (Vikhlinin et al. 1999; Jones et al. 2003) and concluded that these systems are quite abundant. There are, however, only 15 fossil groups known in the literature (table 4 of Mendes de Oliveira et al. 2006). The fact that so few such systems are identified to date is not a surprise. They can easily be mistaken for isolated elliptical galaxies if spectroscopy of the member galaxies is not available, which is often the case. There may also be some known clusters that can fall in the category of fossil groups, as discussed in Section 4.

The main contribution of this paper is to present a new list of fossil groups, obtained from a search in the Sloan Digital Sky Survey database (SDSS Data Release 5 [DR5]), which increases the number of such systems by a factor of 3 and will allow statistical studies on fossil group properties to be done. The search was performed using Structured Query Language and National Virtual Observatory technologies (OpenSkyQuery and Astronomical Data Query Language). We have made use of the ROSAT All-Sky Survey (RASS), since it is the only available X-ray sample with sensitivity and sky coverage large enough to allow performing a search for fossil groups in the SDSS area (although it is known to have limited sensitivity and variable flux limit across the sky). Pointed observations with ROSAT or other satellites do not cover a large enough area.

This paper is structured as follows. In Section 2 we present our definition of a fossil system, as used for the search performed in this paper. Section 3 has our procedures and results, including a description of our selection criteria and of the cross-match with the X-ray data. Section 4 presents a discussion of the results and perspectives. Finally, the Appendix contains the details of the main queries of SDSS databases used in this work.

2. Our Definition of a Fossil System

The definition of a fossil system adopted here is inspired by that of Jones et al. (2003), where the optical image consists of an elliptical galaxy surrounded by fainter companions, so that the difference in the R-band magnitude between the elliptical galaxy and the next brightest companion is ≥ -2 mag. The system should also be detected as an extended X-ray source (in the present case, in the RASS catalog, described in Voges et al. 1999). However, unlike Jones et al. (2003) we do not impose a lower limit on X-ray luminosity. We also consider SDSS r magnitudes, instead of the R-band magnitude adopted by those authors.

Additionally, we consider a fixed value for the search radius around the dominant elliptical galaxy: $0.5h_{70}^{-1}$ Mpc. Jones et al. (2003) consider a search radius of half the projected virial radius (0.5 r_{vir}), which varies for each group. From Khosroshahi et al. (2007), one can verify that, for the fossil groups studied so far, 0.5 r_{vir} varies between 0.22 and 0.68 Mpc, with a median value of 0.48 Mpc.

We do not assume any lower limit for the number of system members. Hence, even an isolated elliptical galaxy may be classified as a fossil system, as long as it is associated with an extended X-ray source.

3. Procedure and Results

In this section we describe all the steps we adopted to search for fossil systems in the SDSS-DR5 (see Adelman-McCarthy et al. 2007).

The SDSS is a photometric and spectroscopic survey, which provides data in a large area of the sky (mainly in the north Galactic cap). It uses a dedicated 2.5 m telescope at Apache Point Observatory in New Mexico. DR5 includes photometric data in five bands (ugriz) for 217 million objects in an area over 8000 deg^2, and 1,048,960 spectra of galaxies, quasars, and stars selected from 5713 deg^2 of the imaging data. DR5 contains all the data from previous data releases and represents the conclusion of the SDSS-I project. The SDSS spectroscopic data contain a magnitude- and color-selected sample of luminous red galaxies (LRGs) for redshifts up to 0.5, selected from cuts in color-magnitude space.

The search was performed in several steps, most of them using SQL (Structured Query Language) in the SDSS SQL database (CasJobs) and ADQL (Astronomical Data Query Language) in the NVO (National Virtual Observatory) tool OpenSky-Query. The queries written in the languages SQL

and ADQL are given in the Appendix.

3.1. Elliptical galaxy selection

We selected galaxies from the LRG catalog (Eisenstein et al. 2001). We consider only objects in this sample with $r < 19$. This restriction ensures that only galaxy companions with $r < 21$ are used to verify whether a system is a fossil or not according to the definition above. The reason is that we are using photometric redshifts to identify the objects associated with the LRGs, and, as discussed by Csabai et al. (2003), they are very uncertain for faint galaxies ($r > 21$), making the identification of system members unreliable. These conditions yield 112,510 galaxies, which corresponds basically to the whole LRG catalog.

Note that not all objects in the LRG sample are ellipticals. Only at the end of our procedure did we select systems dominated by elliptical galaxies through visual inspection of the candidates.

3.2. Cross-match with X-ray data

The cross-match of our LRG sample with the RASS was performed with the function XMATCH in the NVO OpenSkyQuery tool[1] (O'Mullane et al. 2003), which allows us to cross-match astronomical catalogs using a general query language (ADQL, similar to SQL). One can also import a personal catalog of objects and cross-match it against other databases.

In order to obtain correct results from this cross-match, we had to take into account a limitation[2] of OpenSkyQuery: the maximum number of objects for cross-matches between query sets is currently 5000. Consequently, we have divided the 112,510 galaxy sample into subsets of up to 5000 objects. Then each of the subsets was imported into OpenSkyQuery, and the cross-matches were performed with one subset at a time.

The cross-match considers only objects that have extended X-ray emission as measured by RASS, i.e., when the source extent parameter (described in Voges et al. 1999) is larger than 0. The function XMATCH has a parameter, set by the user, which specifies a confidence level for the positional coincidences of the objects in both cata-

[1]openskyquery.net/

[2]http://openskyquery.net/Sky/skysite/help/limitations.aspx

logs. For this parameter, we decided to use a value of 6σ (because of the poor spatial resolution of the ROSAT data). In all cases we checked the reliability of the cross-matched objects once we had the fossil group candidates, and we noted that the distances between the LRG galaxies and the ROSAT extended sources were always less than 0.5 arcmin (see Table 1).

The cross-match yielded 188 LRGs associated with extended X-ray sources. The next step, then, was to analyze the regions around these objects to determine whether they are indeed fossil systems.

3.3. Selection of companions

We have looked for LRG companions within radii of $0.5h_{70}^{-1}$ Mpc (a flag in Table 1 indicates whether the structure would be classified as a fossil if the search radius was $1h_{70}^{-1}$ Mpc). The corresponding angular radii were computed from the LRG spectroscopic redshifts (measured by SDSS) assuming a concordance, zero curvature cosmology with $h = 0.7$, $\Omega_m = 0.3$, and $\Omega_\lambda = 0.7$.

The companions of the cross-matched objects were found using a function in CasJobs called spGetNeighborsRadius, which has the following inputs for each object in a list: identification, right ascension, declination and search-radius (in arcminutes). We have selected companions classified as galaxies by SDSS by considering only objects in the table "Galaxy," which is a subset of the SDSS database that has photometric data for galaxy-type objects.

We have used redshifts to identify the (putative) companions of our LRGs. We used spectroscopic redshifts when available, but for the large majority of the objects we had to use photometric redshifts. The latter, as well as their uncertainties, are described in Csabai et al. (2003), and are now publicly available for all objects in SDSS-DR5 (Adelman-McCarthy et al. 2007).

An object is identified as a companion of a LRG at redshift z_e if its redshift z satisfies the condition:

$$z_e - \Delta z < z < z_e + \Delta z \qquad (1)$$

where Δz is a range in redshift. This range could be, in principle, associated with the group velocity dispersion. However, since the majority of the neighbor galaxies only have photometric redshifts, for which the uncertainties are always larger

than the expected velocity dispersions, we decided to adopt the photometric redshift uncertainty (its median value is 0.035) as the value for Δz.

We adopted a value of $\Delta z = 0.002$ for the few neighbors with spectroscopic redshifts. Note that this value is somewhat restrictive for the companions' selection, but since the final number of fossil system candidates in our sample is small (see below), we decided to allow for false detections to avoid the exclusion of real fossil systems from our sample. In fact, we have repeated the search considering $\Delta z = 0.005$, which decreases the number of fossil systems found at the end of the search (see discussion in section 4).

We decided to consider only neighbors with photometric redshift uncertainties smaller than or equal to 0.1, which is the mean error of photometric redshifts for objects with $r \sim 21$ (Csabai et al. 2003), in order to avoiding large values of these uncertainties affecting our results. Here again we adopted an approach to avoid the exclusion of real fossil systems from the sample at the risk of including a few false ones. The number of galaxies excluded from the analysis for the 34 groups selected, was 13%, on average, of the total number of galaxies in these groups.

3.4. Photometric condition for fossil groups

At this stage of the procedure we have a sample of LRGs with extended X-ray emission and surrounded by putative companions, constrained both spatially (in right ascension and declination) and in redshift. Now we consider the photometric condition that defines fossil systems: the difference in magnitude in the r-band between an elliptical galaxy and the next brightest member should be at least 2 mag. For simplicity this condition is verified for each selected neighbor

$$m_i > m_1 + 2 \tag{2}$$

where m_1 and m_i are the r-band magnitudes of the elliptical galaxy and of the i-th companion. If this condition is satisfied for every companion, the system is classified as a fossil group candidate by our search. From the 188 LRGs, we found 44 that are in systems complying with this photometric condition.

3.5. Analysis of the dominant galaxy

Not all objects in the LRG sample are actually elliptical galaxies, so the next step was to do a visual inspection of the dominant galaxies of these systems to verify whether they are indeed ellipticals. Among the 44 LRGs in the sample of fossil group candidates we found eight systems which do not seem to have elliptical galaxy morphologies (six are spirals and two are mergers), which were then excluded from our fossil group list.

One system had to be dropped from the list because its related X-ray emission turned out to be associated with a strong X-ray white dwarf emitter, which appears as an extended source in the ROSAT catalog.

One first-ranked elliptical galaxy in one of the systems was actually NGC 5846, which, according to the literature (Mahdavi et al. 2005), is part of an isolated group. The group, however, contains one elliptical galaxy (NGC 5813) that is more luminous, indicating that it cannot be a fossil group. The search failed in this case due to the photometric redshift uncertainty of this member (greater than 0.1), which does not have a spectroscopic redshift measured by the SDSS. This group was then also excluded from our list.

The remaining 34 fossil system candidates are presented in Table 1 and Table 2. In Table 1, column 1 presents the fossil group ID number, column 2 the SDSS name of the dominant elliptical galaxy, column 3 the right ascension, column 4 the declination (the coordinates given in the latter two columns are for the central elliptical galaxy, as measured by SDSS) and column 5 the ROSAT name for the source related to the system.

In Table 2, column 1 lists the fossil group ID number, column 2 the spectroscopic redshift of the elliptical galaxy, column 3 its r-band magnitude, column 4 the r-band absolute magnitude, column 5 the radius in arcmin for $0.5h_{70}^{-1}$ Mpc, column 6 the distance between the elliptical galaxy and the ROSAT source, column 7 the X-ray extent, in arcsec, as given in the ROSAT catalog, column 8 gives the X-ray luminosity estimated from the ROSAT count rates, assuming a temperature $kT = 2$ keV and metallicity $Z = 0.4Z\odot$, column 9 lists relevant references in the literature about the elliptical galaxy and column 10 lists relevant related objects from other surveys or catalogs, from the

NASA/IPAC Extragalactic Database (NED).

Note that, although it was not a requirement of the search process, all but one of the first-ranked elliptical galaxies (ID = 28) have $L_R < L_R^\star$. This system has an r-band absolute magnitude of -21.25 while the mean value of all the other systems is -23.74.

By comparing optical luminosities for the dominant elliptical galaxies of our fossil system candidates with elliptical galaxies in low density environments (Colbert et al. 2001; Helsdon et al. 2001; Kelm & Focardi 2004) and in groups (Hickson 1997; Balogh et al. 2004; Kelm et al. 2005; Tanaka et al. 2005; Weinmann et al. 2006; Baldry et al. 2006), we found that our dominant galaxies constitute the bright end of the elliptical galaxy magnitude distribution. In particular, Balogh et al. (2004) and Kelm et al. (2005) show that there is a significant population of luminous elliptical galaxies that are fairly isolated or in low density environments. Therefore, Balogh et al. (2004) conclude that some fraction of the red population must arise independently of environment (e.g., by consumption of the internal gas supply) or they are fossil structures resulting from the complete merging of bright galaxies in a group.

We have estimated the unabsorbed X-ray flux for each fossil system candidate from the count rates in the ROSAT catalog using the tool WebPIMMS[3] and considering a Raymond-Smith model with a temperature of $kT = 2$ keV and metallicity $Z = 0.4$ $Z\odot$, which represent average values for fossil groups (Khosroshahi et al. 2007). Note that our results are not too sensitive to these assumptions. For example, if we use a temperature of $kT = 3$ keV instead, this changes the luminosities by less than 10%. The dependence on the X-ray luminosity on the specific value of metallicity we choose is even weaker.

We have compared the estimated X-ray luminosities of our fossil system candidates with those of groups of galaxies (Ebeling et al. 1994; Pildis et al. 1995; Helsdon & Ponman 2000; Mahdavi et al.

2000; Mulchaey et al. 2003). We found that, although our fossil system candidates show a large dispersion in X-ray luminosities, these tend to be considerably larger than the X-ray luminosities of groups of galaxies. In fact, the X-ray luminosities of our fossil system candidates are, approximately, an order of magnitude larger, on average, than what is found for both compact groups (Ebeling et al. 1994; Pildis et al. 1995; Helsdon & Ponman 2000) and normal groups of galaxies (Helsdon & Ponman 2000; Mahdavi et al. 2000; Mulchaey et al. 2003). On the other hand, our average value for the X-ray luminosity (53.8×10^{42} h_{70}^{-2} erg s^{-1}) is similar to what Khosroshahi et al. (2007) have found for 9 confirmed fossil groups (41.1×10^{42} h_{70}^{-2} erg s^{-1}, bolometric and measured within r_{200}). These results are in agreement with the fact that fossil groups have higher X-ray luminosities, for a given optical luminosity, when compared with normal groups of galaxies (e.g., Khosroshahi et al. 2007).

3.6. Density of fossil groups

The density of fossil systems in the local universe may be computed with the V_{max} technique introduced by Schmidt (1968, see also Felten 1976), which is appropriate for flux-limited samples. With this approach, the density is given by

$$n = \sum_i \frac{1}{V_{max,i}} \qquad (3)$$

and the associated statistical error is

$$\sigma_n = \left(\sum_i \frac{1}{V_{max,i}^2} \right)^{1/2} \qquad (4)$$

where $V_{max,i}$ represents the maximum comoving volume within which the fossil system would remain brighter than the sample limiting flux, and the sum is over all the systems in the sample.

In the present case the detection of fossil systems is determined mostly by the X-rays observations, which are shallower than those in the optical. Since RASS observations do not have a single limiting flux due to the different exposure times of observations across the sky, we have adopted the following procedure. We first identified all extended sources in the RASS catalogue which were observed in fields with exposure times equal to

that of each of the fossil groups listed in Table 1. In order to find the flux limit for a given exposure time, we then estimated, for each source, the flux (using flux2 - see Voges et al. 1999) in the 0.1-2.4 keV energy range, corrected for neutral hydrogen absorption. The flux limit corresponding to a given exposure time was then estimated as the peak of the histogram of fluxes of all sources found in images of the same exposure time. Correcting for the sky coverage of SDSS we obtain a space density of $n = (1.0 \pm 0.6) \times 10^{-6}\ h_{50}^3\ \mathrm{Mpc}^{-3}$. The large error is due to the fact that only 9 systems in our sample have fluxes above the limit corresponding to their exposure times.

The density of fossil groups was also estimated by Jones et al. (2003). From 5 systems with $L_X(0.5\text{-}2\ \mathrm{keV}) > 10^{42}\ h_{50}^{-2}\ \mathrm{erg\ s}^{-1}$ they obtained a density $n \sim 4 \times 10^{-6}\ h_{50}^3\ \mathrm{Mpc}^{-3}$, similar to ours.

Another type of system related to fossil groups are the OLEGs- X-ray overluminous ($L_X(0.5\text{-}2\ \mathrm{keV}) > 2 \times 10^{43}\ h_{50}^{-2}\ \mathrm{erg\ s}^{-1}$) elliptical galaxies (Vikhlinin et al. 1999). The number density of these systems estimated by Vikhlinin et al. (1999) is $n \simeq 2.4 \times 10^{-7}\ h_{50}^3\ \mathrm{Mpc}^{-3}$.

TABLE 1

FOSSIL STRUCTURES: COORDINATES

ID Number	SDSS Name	SDSS RA (J2000)	SDSS DEC (J2000)	ROSAT Name
1[a]	J015021.27-100530.5	01:50:21.3	-10:05:30.5	J015021.2-100537
2[a] [b]	J015241.95+010025.5	01:52:42.0	+01:00:25.6	J015242.1+010040
3[a]	J075244.19+455657.3	07:52:44.2	+45:56:57.4	J075243.6+455653
4[a]	J080730.75+340041.6	08:07:30.8	+34:00:41.6	J080730.4+340104
5[a] [b]	J084257.55+362159.2	08:42:57.6	+36:21:59.3	J084257.7+362141
6	J084449.07+425642.1	08:44:56.6	+42:58:35.7	J084456.2+425826
7[a]	J090303.18+273929.3	09:03:03.2	+27:39:29.4	J090302.8+273939
8[a]	J094829.04+495506.7	09:48:29.0	+49:55:06.7	J094827.2+495523
9	J104302.57+005418.2	10:43:02.6	+00:54:18.3	J104303.0+005423
10[a] [b]	J105452.03+552112.5	10:54:52.0	+55:21:12.5	J105453.3+552102
11[a] [b]	J111439.76+403735.1	11:14:39.8	+40:37:35.2	J111439.4+403735
12[a]	J112155.27+104923.2	11:21:55.3	+10:49:23.2	J112154.2+104936
13[b]	J114128.29+055829.5	11:41:28.3	+05:58:29.5	J114128.4+055827
14[a] [b] [c]	J114647.57+095228.1	11:46:47.6	+09:52:28.2	J114647.4+095236
15[a]	J114803.81+565425.6	11:48:03.8	+56:54:25.6	J114804.1+565410
16[a]	J114915.02+481104.9	11:49:15.0	+48:11:04.9	J114912.9+481058
17[a] [d]	J124742.07+413137.6	12:47:42.1	+41:31:37.7	J124740.1+413128
18[a] [e]	J130009.36+444301.3	13:00:09.4	+44:43:01.3	J130007.7+444251
19[b]	J133559.98-033129.1	13:35:60.0	-03:31:29.2	J133601.0-033147
20[a]	J141004.19+414520.8	14:10:04.2	+41:45:20.9	J141006.4+414520
21[a]	J144516.86+003934.2	14:45:16.9	+00:39:34.3	J144516.1+003918
22	J145359.01+482417.1	14:53:59.0	+48:24:17.1	J145356.9+482418
23	J152946.28+440804.2	15:29:46.3	+44:08:04.2	J152947.4+440755
24[a]	J153344.13+033657.5	15:33:44.1	+03:36:57.5	J153344.0+033717
25[a]	J153950.78+304303.9	15:39:50.8	+30:43:04.0	J153950.3+304305
26	J154855.85+085044.3	15:48:55.9	+08:50:44.4	J154855.0+085102
27[b]	J161431.10+264350.3	16:14:31.1	+26:43:50.4	J161431.2+264336
28[a]	J163720.51+411120.2	16:37:20.5	+41:11:20.3	J163721.3+411106
29[a]	J164702.07+385004.2	16:47:02.1	+38:50:04.3	J164702.5+385003
30[a]	J171811.93+563956.1	17:18:11.9	+56:39:56.1	J171810.9+563955
31[a] [b]	J172010.03+263732.0	17:20:10.0	+26:37:32.1	J172009.3+263727
32[a]	J172852.16+551640.8	17:28:52.2	+55:16:40.8	J172850.5+551622
33[a] [f]	J225630.04-003210.8	22:56:30.0	-00:32:10.7	J225629.8-003231
34[a]	J235815.10+150543.5	23:58:15.1	+15:05:43.6	J235814.4+150524

[a]System is also classified as fossil considering $\Delta z = 0.005$, see text.

[b]System is also classified as fossil considering radius $= 1h_{70}^{-1}$ Mpc, see text.

[c]The elliptical galaxy for this system appears projected onto the cluster ZwCl 1144.3+1010 (it clearly does not belong to the cluster, according to its redshift). In this case, note that the X-Ray emission may be due to the cluster, instead of the fossil system candidate.

[d]The elliptical galaxy is marked as blended, but no deblending attemp was made by SDSS.

[e]The elliptical galaxy is the result of a deblending procedure made in a originally blended object, i. e., it had multiple peaks detected within it.

[f]Same case as (c), the elliptical galaxy is projected onto the cluster ABELL 2505.

Table 2

Fossil Structures: Properties

ID Number	Redshift	r-band Magnitude	r-band Absolute Magnitude	Radius[a] (arcmin)	Distance[b] (arcmin)	X-Ray ROSAT Extent (arcsec)	L_X[c] (h_{70}^{-2}) (erg s^{-1}) (0.5-2keV)	References	Related Objects found in NED
1	0.365	17.26	-24.85	1.641	0.118	44	1.44E+44	...	...
2	0.23	15.72	-24.95	2.269	0.242	58	1.51E+44	1	ABELL 0267
3	0.052	14.46	-22.64	8.241	0.123	10	5.62E+42	2	87GB[d] 074906.3+460432
4	0.208	16.38	-24.05	2.449	0.388	16	4.21E+43	3	FIRST[e] J080730.7+340041
5	0.282	16.79	-24.52	1.951	0.306	63	2.95E+44	4	ABELL 0697
6	0.054	14.08	-22.97	7.919	0.18	37	2.11E+42	5	...
7	0.489	18.06	-25.19	1.38	0.182	37	1.74E+44	...	...
8	0.409	18.21	-24.22	1.529	0.407	10	6.26E+43	...	...
9	0.125	15.98	-23.16	3.704	0.138	25	4.99E+43	5	...
10	0.468	17.69	-25.3	1.415	0.25	13	1.17E+44	...	7C[f] 1051+5537
11	0.202	17.14	-23.16	2.504	0.069	9	4.19E+43	...	...
12	0.24	16.97	-23.84	2.194	0.345	28	3.85E+43	...	...
13	0.188	16.03	-24.11	2.652	0.048	21	2.19E+43	3	NVSS[g] J114128+055828
14	0.221	16.36	-24.24	2.333	0.137	20	4.93E+43	...	...
15	0.105	16.49	-22.08	4.339	0.255	14	1.04E+43	...	...
16	0.283	17.6	-23.66	1.948	0.374	29	6.10E+43	...	...
17	0.155	15.88	-23.7	3.093	0.403	14	6.25E+42	...	...
18	0.233	16.88	-23.8	2.243	0.342	20	2.63E+43	...	...
19	0.177	15.84	-24.14	2.787	0.396	36	3.68E+43	...	...
20	0.094	14.66	-23.64	4.781	0.413	10	2.96E+42	5	...
21	0.306	17.94	-23.65	1.843	0.326	35	7.21E+43	...	...
22	0.146	15.87	-23.58	3.255	0.351	29	5.75E+42	...	...
23	0.148	15.77	-23.71	3.224	0.252	13	1.10E+43	5	...
24	0.293	17.23	-24.21	1.902	0.335	41	6.00E+43	...	...
25	0.097	14.93	-23.5	4.636	0.106	62	4.86E+43	6	FIRST[e] J153950.7+304303 , ABELL 2110
26	0.072	13.5	-24.25	6.06	0.362	59	5.09E+42	7	UZC[h] J154855.9+085045
27	0.184	15.76	-24.36	2.693	0.232	19	2.37E+43	...	...
28	0.032	14.51	-21.25	13.153	0.274	17	4.16E+41	8	...
29	0.135	16.13	-23.09	3.48	0.083	27	6.87E+42	6	FIRST[e] J164702.0+385005
30	0.114	15.27	-23.55	4.037	0.144	68	4.67E+43	5, 3, 9, 10	ZwCl[i] 1717.9+5636 , 7C[f] 1717+5643
31	0.159	15.44	-24.33	3.03	0.181	62	1.77E+44	5, 3, 10	...
32	0.148	16.72	-22.81	3.214	0.393	14	3.53E+42	...	...
33	0.224	16.81	-23.91	2.314	0.351	15	2.18E+43	6	FIRST[e] J225630.0-003209
34	0.178	16.08	-23.98	2.763	0.369	21	9.26E+42	...	...

[a] Equivalent to the radius $0.5 h_{70}^{-1}$ Mpc.

[b] Distance between the SDSS elliptical galaxy and its ROSAT counterpart.

[c] X-ray luminosity estimated from ROSAT count rates, assuming a temperature $kT = 2$ keV and metallicity $Z = 0.4 Z_\odot$.

[d] 1987 Green Bank Radio Survey.

[e] Faint Images of the Radio Sky at Twenty Centimeters.

[f] Seventh Cambridge Radio Catalog.

[g] NRAO VLA Sky Survey.

[h] Updated Zwicky Catalog.

[i] Zwicky's Catalog of Galaxies and Clusters of Galaxies.

References. — (1) Plionis et al. 2005; (2) Véron-Cetty & Véron 2001; (3) Best et al. 2005; (4) Metzger & Ma 2000; (5) Merchán & Zandivarez 2005; (6) Brinkmann et al. 2000; (7) Falco et al. 1999; (8) Rines et al. 2002; (9) Hao et al. 2005; (10) Prada et al. 2003.

4. Discussion

The search for fossil groups performed in this work was intended to be as inclusive as possible, minimizing the probability of exclusion of real fossil systems from our sample. It should then be noted that our procedure leads to an increase in the probability of having false fossil systems in our final list. The conditions considered throughout the search, such as small values for the system radius and for the minimum redshift range constraint, tend to decrease the number of companions around the elliptical galaxies, which in turn increases the probability of fossil system detection, since there are fewer galaxies subjected to the photometric condition for a system to be a fossil. For the final results, we decided to adopt $0.5h_{70}^{-1}$ Mpc for the radius around the luminous elliptical galaxies and 0.002 for the minimum redshift range constraint. This gave us a final list with 34 groups, which are listed in tables 1 and 2.

We have re-done the same procedure considering another value for the search radius, namely $1h_{70}^{-1}$ Mpc. We found that the search yields only 9 fossil systems for $1h_{70}^{-1}$ Mpc and when the redshift range is 0.002. A total of 26 fossil systems are found when we consider $0.5h_{70}^{-1}$ Mpc and, instead, a minimum redshift range of 0.005. For the most restrictive case, i. e., a search radius of $1h_{70}^{-1}$ Mpc and the minimum redshift range of 0.005, we only find 6 fossil systems. Therefore, the number of fossil system candidates depends critically on these parameters. Table 1, which presents the fossil system candidates, shows flags indicating whether the system is also classified as a fossil in those two other scenarios.

In this work, in order to identify galaxies spatially close to the elliptical galaxy, we used photometric redshifts, for which uncertainties are known to be high in comparison with those of spectroscopic redshifts. Thus, even considering only companion galaxies with r-band magnitude less than 21 and excluding galaxies with photometric redshift uncertainty larger than 0.1 (see section 3.3), the photometric redshift accuracy does limit the efficiency of the search. However, for the kind of search conducted here, where a large survey such as SDSS is required, the use of photometric redshifts is the only viable way to find structures around the elliptical galaxies.

We would like to note that no redshift cut was applied to the sample. The highest redshift fossil group found was at z=0.47 (system with ID = 10).

4.1. Other classifications for the fossil groups

We performed a search in the NED[4] for each of the 34 fossil system candidates found in this work, in order to find additional information on them. Specifically, we looked for related objects in other surveys/catalogs and scientific papers that cite the elliptical galaxies of the fossil systems. These are listed in Table 2.

We found that eight fossil system candidates (IDs = 3, 4, 10, 13, 25, 29, 30, 33) are related to radio emission sources, from different surveys (listed in Table 2). Four systems (IDs = 4, 13, 30, 31) were classified as radio-loud active galactic nuclei (AGNs), described in Best et al. (2005). One of the systems (ID = 30) was also selected as an AGN in Hao et al. (2005). In addition, one system (ID = 3) is part of a catalogue of quasars and active nuclei, described in Véron-Cetty & Véron (2001). It is worth noting that the soft X-ray luminosity of these fossil system candidates might be contaminated by non resolved central AGNs.

Six systems (IDs = 6, 9, 20, 23, 30, 31), out of the 34 fossil system candidates, were classified as galaxy groups by Merchán & Zandivarez (2005). In that paper, they used a spectroscopic galaxy sample from SDSS-DR3 (Third Data Release) to produce a group catalog, using a method based on the friends-of-friends algorithm.

We also found that four systems from our list (IDs = 2, 5, 26, 30) may belong to galaxy clusters. In particular, our search in NED indicates that system 5 is related to the cluster ABELL 0697 and system 2 is related to ABELL 0267. The systems with IDs = 26, 30 are classified as clusters in the Zwicky catalog (Falco et al. 1999).

4.2. Cross-check with the list of previously known fossil groups

We have cross-checked our results with the list of known fossil groups presented in Mendes de Oliveira et al. (2006). Out of the 15 known fossil groups, SDSS has no available data for six of them, and in seven

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[4]http://nedwww.ipac.caltech.edu/

others their main elliptical galaxies had no measured spectra in SDSS; thus, they were not selected in the first step of the search. The elliptical galaxies of the remaining two (RX J1159.8+5531; RX J1340.6+4018) were classified as LRG with measured spectroscopic redshifts, but were not selected in the cross-match with ROSAT performed in OpenSkyQuery.

We decided to search in the RASS catalog for X-ray sources related to those two known fossil groups, but in an independent way. We used ROSAT tool Source Browser[5] for the search, using the coordinates given in Mendes de Oliveira et al. (2006).

For the fossil group RX J1159.8+5531 (Vikhlinin et al. 1999), at $11^h59^m51\overset{s}{.}4, 55°32'01''$, the nearest extended source has the coordinates $11^h57^m56\overset{s}{.}10, 55°27'17''\!.5$ which gives a distance of ~ 17 arcmin, much greater than expected for the occurence of a cross-match in OpenSkyQuery. However, there is a nearer (distance ~ 0.6 arcmin) point-like source (ext = 0) at $11^h59^m55\overset{s}{.}40, 55°31'53''\!.0$. In the original paper (Vikhlinin et al. 1999), they found that the isolated elliptical galaxy lies exactly at the peak of the X-ray emission (see their Fig. 1).

For RX J1340.6+4018 (Ponman et al. 1994), whose coordinates are $13^h40^m33\overset{s}{.}4, 40°17'48''$, we found the nearest extended source at $13^h40^m38\overset{s}{.}10, 40°36'39''\!.5$, which represents a distance of ~ 19 arcmin, again too large to have a cross-match in OpenSkyQuery. The nearest point-like source is at a distance of ~ 7.6 arcmin, at $13^h41^m02\overset{s}{.}60, 40°12'38''\!.0$. According to Ponman et al. (1994), the X-ray emission centroid coincides with the elliptical galaxy within 10 arcseconds (see their Fig. 1).

The discrepancies found between RASS extended X-ray sources and the X-ray emission detected for those known fossil groups may be due to differences in spatial resolution between the ROSAT All-Sky Survey catalog and the pointed observations performed by those authors (Ponman et al. 1994; Vikhlinin et al. 1999). The uncertainties of the extended source centers in the ROSAT catalog can also affect our cross-match results.

In addition, even if the cross-match had been succesful for RX J1340.6+4018, it still would not be considered a fossil system in our search. Ac-

cording to SDSS, there is a bright galaxy with measured concordant spectrocopic redshift at $13^h40^m37\overset{s}{.}64, 40°15'16''\!.3$, thus inside the radius of $0.5h_{70}^{-1}$ Mpc (distant ~ 2.6 arcmin). The difference in r-band between this galaxy and the central one is 1.3 and $\Delta z = 0.002$. However, when considering the original definition of fossil groups by Ponman et al. (1994) and Jones et al. (2003), RX J1340.6+4018 is indeed a fossil system because that galaxy (at $13^h40^m37\overset{s}{.}64, 40°15'16''\!.3$) lies outside the half virial radius (around 270 kpc in this case).

4.3. Perspectives

There are several open questions in the study of the formation and evolution of fossil groups, which can be tackled using the sample catalogued here. We discuss below two studies which can be performed using our sample: (1) the determination of ages, metallicities and abundances of the first-ranked galaxies in fossil groups and (2) the determination of the luminosity function of fossil group galaxies. Motivation and more details of these studies are given in the following.

- (1) The morphology of the first-ranked galaxies in seven fossil groups was investigated by Khosroshahi et al. (2006a), from R-band and near infrared images and none of the galaxies were found to have boxy isophotes, in contrast with results found for brightest cluster galaxies (BCGs). This suggests that the brightest galaxies in fossil groups may have a different structure than that of BCGs. In fact, Khosroshahi et al. (2007, astro-ph/0702095) concluded that there is an absence of recent merging in fossil groups and D'Onghia et al. (2005) suggested that fossil groups have assembled 50% of their masses at z > 1 and have grown through minor mergers at later stages. It would be most useful to have determinations of ages/metallicities and alpha enhancements of the central elliptical galaxies of fossil groups but so far no spectroscopic analysis of such galaxies has been made. Our sample offers a prime chance to do such an analysis, since spectra are available for all first-ranked galaxies of the 34 fossil groups catalogued here through the SDSS database.

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[5]http://www.xray.mpe.mpg.de/cgi-bin/rosat/src-browser

- (2) D'Onghia & Lake (2004) argued that fossil groups have two orders of magnitude less substructure than predicted in CDM cosmological simulations. The significance of this result, however, depends on a reliable determination of the galaxy luminosity function of fossil groups, which was not available at the time of that study. Recently, two rich fossil groups, RX J1552.2+2013 and RX J1416.4+2315 have been studied spectroscopically and their luminosity functions determined down to M=-18 (Mendes de Oliveira et al. 2006; Cypriano et al. 2006). For RX J1552.2+2013 the luminosity function shows a lack of faint galaxies, with $\alpha = -0.6$. For RX J1416.4+2315 the spectroscopic luminosity function was measured with lower accuracy, to have a value with the faint end well fit by $\alpha = -1.2$, compared with $\alpha = -0.6$ measured for the LF of the same group (by Khosroshahi et al. 2006b). More fossil groups have to be studied in detail for a better understanding of the shapes of the luminosity functions of these systems, specially at the faint end. The sample cataloged here may be useful for such studies, as more measurements of redshifts for the possible group members are obtained.

A. SQL and ADQL Queries

Note that only the main queries are listed here.

SQL query to select luminous red galaxies from SDSS:
```
SELECT
    p.objID, s.ra, s.dec, s.z as redshift, p.u, p.g, p.r, p.i, p.z,
    (p.u-p.r) as u_r, l.ew as d4000, s.eClass, p.lnlDev_r,
    p.lnlExp_r INTO lrgs
FROM SpecObj as s, Galaxy as p, SpecLineIndex as l
WHERE
    s.bestObjID = p.objID AND
    s.specClass = 2 AND
    s.zStatus > 1 AND
    (s.primTarget & 0x00000020 > 0) AND
    s.z > 0 AND p.r < 19 AND
    l.specobjid = s.specobjid AND
    l.name = '4000Abreak'
ORDER BY p.objID
```

ADQL query on OpenSkyQuery that performs the cross-match between LRG galaxies and ROSAT extended objetcs:
```
SELECT x.objid, x.ra, x.dec, x.ext, t.*
FROM Rosat:PhotoPrimary x, MyData:lrgs_1 t
WHERE XMATCH(x, t) < 6 AND x.ext > 0
```

SQL queries to select neighbors around the elliptical galaxies:
```
CREATE TABLE neighbors (
    ra float,
    dec float,
    rad float,
    id int,
    z float,
    objid bigint,
    r real
)
CREATE TABLE #UPLOAD(
    up_ra FLOAT,
    up_dec FLOAT,
    up_rad FLOAT,
    up_id int
)
INSERT INTO #UPLOAD
SELECT
    ra AS UP_RA,
    dec AS UP_DEC,
    rad as UP_RAD,
    id AS UP_ID
FROM mydb.radius
```

```
ORDER BY id
CREATE TABLE #tmp (
    up_id int,
    objid bigint
)
INSERT INTO #tmp
EXEC spGetNeighborsRadius


INSERT INTO mydb.neighbors
SELECT a.ra, a.dec, a.rad, a.id, a.redshift, t.objid, g.r
FROM #tmp t, mydb.radius a, Galaxy g
WHERE t.up_id = a.id AND t.objid = g.objID AND g.r < 21
ORDER BY a.id, t.objid
```

SQL Query to select photometric redshifts of the neighbors:
```
SELECT n.id, n.objid, p.z, p.zErr, p.quality, n.r
INTO redshifts
FROM neighbors as n, dr5.photoz as p
WHERE n.objid = p.objid
ORDER BY n.id, n.objid
```

SQL queries to replace photometric redshifts with spectroscopic ones when available:
```
UPDATE redshifts
SET z =
    (SELECT TOP 1 d.z
    FROM dr5.specObj as d
    WHERE d.bestObjID = redshifts.objID AND d.zStatus > 1 AND d.z > 0)
WHERE EXISTS
    (SELECT TOP 1 d.z
    FROM dr5.specObj as d
    WHERE d.bestObjID = redshifts.objID AND d.zStatus > 1 AND d.z > 0)
UPDATE redshifts
SET zErr = 0.002
WHERE EXISTS
    (SELECT top 1 d.zErr
    FROM dr5.specObj as d
    WHERE d.bestObjID = redshifts.objID AND d.zStatus > 1 AND d.z > 0)
```

SQL query to exclude objects that have large redshift uncertainty:
```
DELETE
FROM redshifts
WHERE zErr > 0.1
```

SQL query to constrain systems using redshifts:
```
SELECT s.* INTO groups FROM redshifts as s, lrgs as t
WHERE
    s.id = t.id AND
    (s.z BETWEEN (t.redshift - s.zErr) AND (t.redshift + s.zErr))
```

```
ORDER BY s.id, s.objid
```

SQL query to identify non-fossil systems:

```
SELECT s.* INTO nofossils
FROM lrgs as l, groups as s
WHERE s.id = l.id AND (s.r <= (l.r + 2))
ORDER BY s.id, s.objid
```

SQL query that deletes non-fossil systems, leaving only fossil systems candidates in the table:

```
DELETE FROM fossils
WHERE EXISTS
    (SELECT *
    FROM nofossils as g
    WHERE g.id = fossils.id)
```

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